Environmental Research 132 (2014) 305–310

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Characterizing the impact of traffic and the built environment on near-road ultrafine particle and black carbon concentrations

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ARTICLE INFO

Article history:
Received 23 October 2013
Received in revised form
7 April 2014
Accepted 9 April 2014
Available online 14 May 2014

Keywords:
Ultrafine particles
Black carbon
Traffic
Built environment

ABSTRACT

Background: Increasing evidence suggests that ultrafine particles (UFPs) may contribute to cardiorespiratory morbidity. We examined the relationship between near road UFPs and several traffic and built environment factors to identify predictors that may be used to estimate exposures in population-based studies. Black carbon (BC) was also examined.
Methods: Data were collected on up to 6 occasions at 73 sites in Montreal, Canada over 6-week period during summer, 2012. After excluding highly correlated variables, road width, truck ratio (trucks/total traffic), building height, land zoning parameters, and meteorological factors were evaluated. Random-effect models were used to estimate percent changes in UFP and BC concentrations with interquartile changes in each candidate predictor adjusted for meteorological factors.
Results: Mean pollutant concentrations varied substantially across sites (UFP range: 1977–94, 798 particles/cm^3; BC range: 29–9460 ng/m^3). After adjusting for meteorology, interquartile increases in road width (14%, 95% CI: 0, 30), building height (13%, 95% CI: 5, 22), and truck ratio (13%, 95% CI: 3, 23) were the most important predictors of mean UFP concentrations. Road width (28%, 95% CI: 9, 51) and industrial zoning (18%, 95% CI: 2, 37) were the strongest predictors of maximum UFP concentrations. Industrial zoning (35%, 95% CI: 9, 67) was the strongest predictor of BC.
Conclusions: A number of traffic and built environmental factors were identified as important predictors of near road UFP and BC concentrations. Exposure models incorporating these factors may be useful in evaluating the health effects of traffic related air pollution.

1. Introduction

Traffic emissions are an important source of air pollution exposures in urban environments and have been associated with a number of adverse health effects including cardiorespiratory morbidity, mortality, and cancer (Beckerman et al., 2012; Berflind et al., 2009; Chen et al., 2013; Crouse et al., 2010; Jerrett et al., 2009; Parent et al., 2013; von Klot et al., 2011). In general, ambient nitrogen dioxide (NO$_2$) has been used as a marker of traffic-related air pollution in large-scale epidemiological studies owing to the availability passive samplers and exposure models (e.g. land use regression) that can be used to estimate exposures for large numbers of study participants (Crouse et al., 2009; Jerrett et al., 2009). However, it is generally recognized that NO$_2$ is a surrogate measure of a broader mixture of traffic-related air pollution and that NO$_2$ itself may not be the etiological agent of interest (Brook et al., 2007). More recently, ultrafine particles (UFPs) have received increased attention as vehicle emissions are an important source of these pollutants and existing evidence suggests that short-term exposures to UFPs may have a measureable impact on cardiorespiratory morbidity (Ibald-Mulli et al., 2002; Weichenthal, 2012). However, there are no studies of the long-term health impacts of UFPs owing in part to the absence of exposure assessment models capable of assigning exposures to participants over a broad geographic area (HEI, 2013). In particular, exposure models capable of estimating pollutant concentrations at the local level (e.g. home addresses) are required given the high spatial variability of urban UFPs and their rapid decay from near roadway

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Abbreviations: IQR, interquartile range; LUR, land use regression; PIP, Posterior Inclusion Probability; UFP, ultrafine particles

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http://dx.doi.org/10.1016/j.envres.2014.04.007

peaks (Karner et al., 2010). To date, land use regression models have been developed for UFPs in Vancouver, Canada (Abernethy et al., 2013), Amsterdam, Netherlands (Hoek et al., 2011), and Girona, Spain (Rivera et al., 2012), and findings generally suggest that models based on traffic parameters, land use, and local sources can be used to estimate the spatial distribution of UFP concentrations in urban areas. Here we evaluate a number of predictors that may be useful in developing similar models for Montreal, Canada. Specifically, this study aimed to characterize the magnitude of associations between near roadway UFPs and black carbon (BC) concentrations and traffic and built environment factors that may serve as determinants of exposure in population-based studies.

2. Methods

2.1. Air pollution monitoring

UFP (0.01–1 μm) (TSI CPC Model 3007) and BC (Magee Scientific, Micro-aethalometer) data were collected at 73 sites along a range of roadways in Montreal, Canada over a 6-week period between June and July, 2012. Monitoring sites were identified as part of a larger data collection effort aimed at capturing air pollutant concentrations along roadways in Montreal. Specifically, maps of the road network including information on road geometry (width, number of lanes, and classification) and traffic flows at 1841 intersections in Montreal were used to select sites in an effort to maximize variations in the set of determinant variables available for analysis. The data include traffic counts conducted at 15 min intervals at each intersection for 8 h during the day. These counts were conducted in 2009 and 2010 and range from 200 to 6000 vehicles/h at each location. We did not adopt a particular algorithm to achieve this allocation but we manually identified the locations in a way that allowed us to achieve variability in the parameters of interest. Our data collection sites were selected to reflect diversity in both traffic volumes and road types. While the City of Montreal database includes only local and arterial roads, we added bridges to our sample of sites in order to achieve better representation of the road network. All measurements were recorded at the side of the road as close as possible to the roadway (little variability was observed in terms of distance from curb). Technicians also measured the distance between monitoring locations and the centerline of each road; however, this measurement was generally equivalent to half of the road width and thus it was not retained for analysis as it simply duplicated information already captured by the road width variable.

Two pairs of research assistants collected simultaneous UFP, BC, and traffic information at each monitoring site. Research assistants manually recorded vehicle composition at each location for the duration of each air monitoring period. Traffic composition data included cars, light-duty trucks (SUVs, vans, pick-up trucks), heavy-duty trucks, buses, motorcycles, total traffic, and the ratio of trucks to total traffic. Real-time UFP and BC data were collected using the above instrumentation at 1-s sampling intervals using instruments carried in backpacks with sampling tubes placed in technicians' breathing zones. All measurements were recorded over 10–20 min periods on sidewalks at mid-block; data were collected at each location during peak morning (8–10 AM) and afternoon (3–5 PM) periods as well as during mid-day (11 AM–2 PM). Each location was monitored on at least 3 separate occasions (typically 1–2 weeks apart) up to a maximum of 6 times. Meteorological data were extracted from Environment Canada's online database for the duration of each air monitoring period (McTavish station for downtown locations and Trudeau airport station for suburban locations).

All BC data were processed prior to computing descriptive statistics owing to the fact that the microaethalometer sometimes outputs negative observations when the difference in light attenuation between two consecutive readings is negligible. In particular, an optical noise-reduction averaging algorithm was used to correct the readings (Hagler et al., 2011). Briefly, this algorithm reads the difference in light attenuation between consecutive readings and eliminates peaks in BC concentrations associated with a light attenuation differential below 0.05. The algorithm then averages BC data across time intervals associated with changes in incremental light attenuation of 0.05. After applying this algorithm the mean sampling interval for black carbon measurement was 2.6 min; however, values used for analysis in this study reflect BC vales averaged over the entire sampling interval at each site (10–20 min).

2.2. Built environment data collection

Road geometry and built environment data surrounding each air monitoring location were compiled using a combination of GIS databases, Google maps, and orthophotographs. Most processing was conducted in ArcGIS (ArcMap10, ESRI Inc.) using automated buffering and intersecting functions. Compiled variables included characteristics of each road segment where monitoring was conducted as well as land-use and built environment factors within a buffer around monitoring points (described below).

2.3. Statistical analysis

Spearman's correlations were first used to evaluate potential co-linearity between candidate predictors related to traffic and the built environment. If two predictors were moderately or highly correlated ($r > 0.50$), the predictor that could be most easily measured at the local level (e.g. home address) was retained for analysis. This approach was selected as the ultimate goal was to identify factors that could be included in future models designed for application in large-scale epidemiological studies where detailed information on specific predictors may not be available.

Random-effects models were first used to estimate the relationship between air pollution concentrations (mean and maximum UFP concentrations and mean BC concentrations) and each traffic/built environment factor separately. These models included a random intercept for monitoring site (i.e. measurements nested within site) to account for potential correlations between repeated air pollution measurements collected at the same location but a different time-points. We previously employed a similar approach to characterize the impact of traffic and built environment on air pollution exposures over repeated cycling trips in Montreal (Hatzopoulou et al., 2013). In this study, the following traffic and built environment factors were evaluated in random-effects models: traffic counts (buses, cars, trucks, SUV/vans, motorcycles, total traffic), road width (m), number of traffic lanes, buildings on both sides of the street, continuous buildings on both sides of the street, mean building height (with a 25 m buffer), building coverage (within a 25 m buffer), and several zoning factors (percentage commercial, industrial, institutional, residential, park, and undeveloped land) within a 150 m buffer of each monitoring site. All air pollution data were log-transformed for statistical modeling and all coefficients reflect percent changes air pollution concentrations per interquartile range (IQR) increase in predictor variables. All models were adjusted for continuous measures of average ambient temperature and wind speed during sampling.

Covariates for final multi-variable random-effects models were selected using approximate Bayes factors calculated using the BMS package (Feldkircher and Zeugner, 2009) in R (version 2.15.3) with uniform model priors (which assumes that all models are equally likely *a priori*) and non-informative "unit information" priors for model coefficients which contain the information equivalent to one observation. Bayes Factors calculate the probability of obtaining the observed data under each possible model, with higher Bayes Factors going to models that would more likely lead to the observed data. This process considers models for all possible combinations of the predictor variables examined. Specifically, when comparing two models, say model 1 and model 2, Bayes Factors are defined as the probability of the data given model 1 divided by the probability of the data given model 2, these probabilities averaged over the prior density of each unknown parameter in the model (Kass and Raftery, 1995). Thus, Bayes Factors larger than one indicate better fit for model 1, while Bayes Factors below one indicate better fit for model 2. Bayes Factors lead to the probability of including the parameter in the model (Posterior Inclusion Probability (PIP)) which is an indication of the overall utility of this variable in making future predictions. Bayes Factors have also been shown to avoid over-fitting the data and lead to optimal future predictions in future samples (Kass and Raftery, 1995). PIPs for a given predictor variable represent the sum of posterior model probabilities for all models in which a covariate was included, with the most important predictors having the highest PIPs. Candidate predictors with the highest PIPs ($>50\%$) were automatically included in final multivariable random-effects models. Other predictors were also evaluated if they had a meaningful impact (a change of at least 10%) on air pollution concentrations in single predictor models (described above). These factors were retained if their coefficients suggested a meaningful impact (a change of at least 10%) on air pollutant concentrations regardless of statistical significance. Continuous measures of average ambient temperature and wind speed were also included in all final models. All random-effects models were estimated using the *xtmixed* procedure in STATA (version 11; StataCorp LP, College Station, TX, USA).

As a sensitivity analysis, an alternative approach was also examined to account for potential correlations in repeated measurements collected at each sampling location. Specifically, final random-effects models (described above) were also run using marginal mixed-effects models with a first order autoregressive (AR-1) residual covariance structure to account for potential correlations in repeated measurements collected at each location over time (*xtgee* procedure in STATA). This covariance structure specifies that measurements collected closer in time are more highly correlated, with correlations decreasing with time between measurements. All mixed-effects models were estimated using the *xtgee* procedure in STATA (version 11; StataCorp LP, College Station, TX, USA).

3. Results

In total, UFP data were collected at 73 locations and valid BC data were obtained at 61 sites. Monitoring sites included 47 locations in the downtown core, 24 locations outside the downtown core (on the periphery or in the suburbs), and 2 points located along bridges connecting the Island of Montreal with the rest of the region. Eighty-five observations were collected in the morning peak period, 73 in the afternoon peak period, and 56 during off-peak hours. Traffic flows at the selected locations ranged from 80 to approximately 6000 vehicles per hour (Fig. 1). The proportion of heavy-duty trucks did not exceed 30% of the total traffic flow with the majority of sites recording less than 3% of heavy-duty trucks.

Average ambient temperature and wind speed during monitoring ranged from 14 to 33 °C and 2 to 13 km/h respectively, and reflected typical conditions in Montreal during the summer months. Descriptive data for air pollutant concentrations and traffic/built environment factors are summarized in Table 1. Mean UFP levels varied substantially across the island of Montreal with number concentrations ranging from less than 2000 cm^{-3} to more than 90,000 cm^{-3}. Maximum UFP concentrations and mean BC concentrations also varied substantially between sites. Mean ultrafine

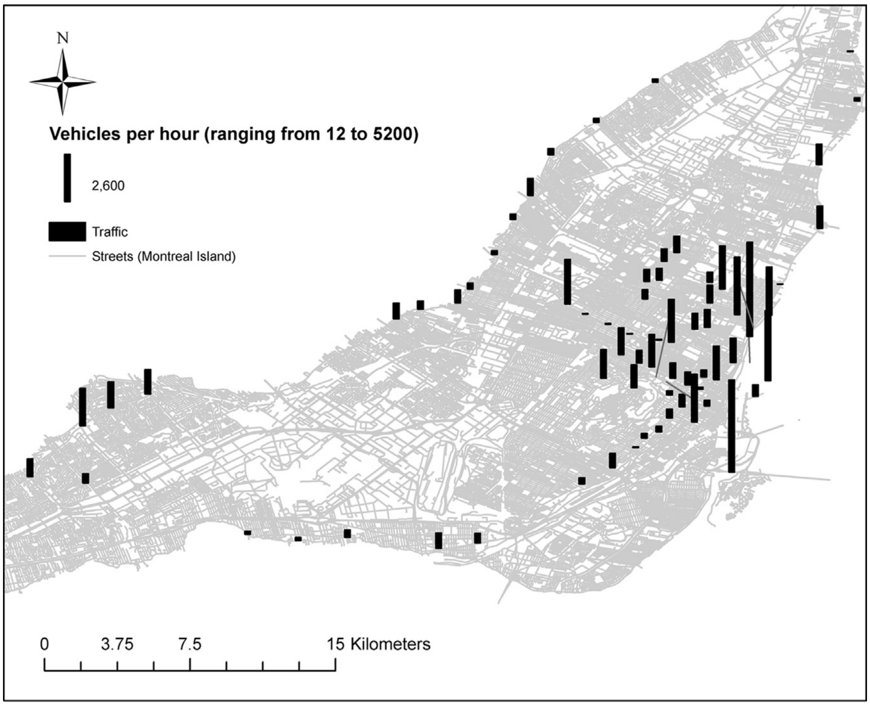

Fig. 1. Traffic volumes at each data collection site.

Table 1
Summary of air pollutant concentrations, traffic, and built environment measures.

	Mean/% (SD)	Minimum	Maximum	Sites (*n*)	Samples (*n*)
Mean UFP (#/cm^3)	20,145 (14,000)	1977	94,798	73	200
Maximum UFP (#/cm^3)	77,863 (55,486)	2368	214,561	73	200
Mean black carbon (ng/m^3)	1140 (1260)	29	9460	61	103
Traffic counts (per 10 min)					
Cars	102 (121)	0	694	73	214
Trucks	7.4 (15)	0	84	73	214
SUV/vans	53 (59)	0	318	73	214
Buses	2.5 (4.0)	0	39	73	214
Motorcycles	1.5 (2.4)	0	19	72	179
Total traffic count	195 (192)	0	1074	73	214
Truck ratio	0.028 (0.036)	0	0.26	73	214
Number of traffic lanes	2.9 (2.0)	1	8	73	214
Road width (m)	9.8 (6.7)	2.6	28	73	214
Buildings on both sides	52%			73	214
Continuous buildings	20%			73	214
Building coverage (%)[a]	14% (14)	0	51%	73	214
Mean building height (m)[a]	2.6 (4.8)	0	29	62	177
Commercial zoning (%)[b]	3.8% (7.2)	0	38%	73	214
Industrial zoning (%)[b]	11% (15)	0	64%	73	214
Institutional zoning (%)[b]	8.4% (14)	0	68%	73	214
Undeveloped area (%)[b]	3.1% (5.7)	0	34%	73	214
Park zoning (%)[b]	11% (26)	0	100%	73	214
Residential zoning (%)[b]	56% (30)	0	100%	73	214

SD, standard deviation.

[a] Within a 25 m buffer.

[b] Within a 150 m buffer.

Table 2
Random-effect models for UFPs, black carbon and traffic and built environment factors.

Independent variable	IQR	Percent change mean UFP per IQR (95% CI)	Percent change maximum UFP per IQR (95% CI)	Percent change black carbon per IQR (95% CI)
Road width (m)	6.6	14% (0, 30)	31% (10, 55)	15% (−10, 47)
Truck ratio (%)	2.9	12% (4, 20)	18% (6, 30)	21% (1, 46)
Industrial zoning (%)[a]	14	12% (0, 25)	21% (4, 41)	37% (12, 69)
Mean building height (m)[b]	2.8	10% (2, 20)	8.7% (−3, 21)	3.2% (−12, 21)
Undeveloped area (%)[a]	4.0	7.6% (0, 17)	6.0% (−5, 18)	13% (−4, 32)
Institutional zoning (%)[a]	14	6.3% (−6, 20)	7.9% (−8, 27)	−9.4% (−28, 13)
Commercial zoning (%)[a]	5.5	4.5% (−5, 15)	10% (−3, 25)	1.2% (−15, 20)
Park zoning (%)[a]	9.7	−0.21% (−6, 6)	5.9% (−1, 14)	−1.0% (−11, 10)
Residential zoning (%)[a]	43	−14% (−29, 4)	−28% (−44, −9)	−17% (−41, 19)

IQR, interquartile range. Each factor was evaluated separately in models adjusted for ambient temperature and wind speed.

[a] Within a 150 m buffer.

[b] Within a 25 m buffer.

particle and black carbon concentrations were weakly correlated ($r=0.35$).

A number of traffic/built environment predictors were highly correlated and thus were removed from further analysis in random-effect models. Specifically, road width was highly correlated with all traffic count variables ($0.60 \geq r \leq 0.79$) and number of traffic lanes ($r=0.95$); therefore, only road width was retained for analysis as an indicator of traffic volume. To verify this decision, we compared coefficients for road width and total traffic counts in single predictor models. In general, coefficients for interquartile changes in road width and total traffic counts were comparable in magnitude (data not shown) with the exception of models for maximum UFP concentrations. In these models, the coefficient for road width (28%, 95% CI: 9, 51) was more than double the coefficient for traffic counts (12%, 95% CI: −3, 29). Indicator variables for the presence of buildings on both sides of the street and continuous buildings on both sides of the street were also removed from analysis owing to correlations with building coverage ($r > 0.51$). Moreover, building coverage was correlated with average building height ($r=0.69$) and inversely correlated with road width ($r=-0.62$); therefore, average building height was retained for analysis. In total, 9 variables were retained for evaluation in multivariable random-effects models including: road width, truck ratio (trucks/total traffic counts), mean building height within a 25 m buffer, and six zoning factors within a 150 m buffer (commercial, industrial, institutional, undeveloped, park, and residential).

Random-effect models for individual candidate predictors are shown in Table 2. Road width was the strongest predictor of mean and maximum UFP concentrations with each IQR increase in road width corresponding to 14% (95% CI: 0, 30) and 31% (95% CI: 10, 55) increases in mean and maximum UFP concentrations, respectively. Truck ratio and industrial zoning were positively associated with mean and maximum UFP concentrations and these factors were also the strongest predictors of mean BC concentrations. Residential zoning was inversely associated with UFPs and BC with the strongest association observed for maximum UFP concentrations. Similarly, mean building height was positively associated with air pollutant concentrations but was most strongly associated with mean UFPs. Ambient temperature and wind speed were each inversely associated with near road air pollution concentrations (Table 3), likely owing to decreased volatility (i.e. less evaporation of the volatile component of particulate matter) and increased mixing at lower temperatures and higher wind speeds, respectively.

Final multivariable models describing the impact of traffic/built environment factors on UFP and BC concentrations are shown in Table 3. Of the factors examined, road width, mean building height, and truck ratio were identified as the most important predictors of mean UFP concentrations. Coefficients for these variables were similar to those in single predictor models with each associated with increases of more than 10% per interquartile change after adjusting for meteorological factors. Industrial and residential zoning were also explored as potential predictors of mean UFPs in final multivariable models based on strong associations in single predictor models; however, the magnitudes of these associations decreased in multivariable models and thus were not included in the final model. Potential interactions between road width and mean building height were also examined in the final model for mean UFPs by including a first order integration term; however, we did not observe a significant interaction between road width and building height ($p=0.561$).

Table 3
Multivariable random-effect models for air pollutant concentrations and traffic and built environment factors.

Model	PIP (%)	IQR	Percent change per IQR (95% CI)
Mean UFP concentration (particles/cm^3)			
Road width (m)	57	6.6	14% (0, 30)
Mean building height (m)[a]	87	2.8	13% (5, 22)
Truck ratio (%)	78	2.9	13% (3, 23)
Wind speed (km/h)	75	3.0	−9.8% (−20, 2)
Temperature (°C)	98	4.7	−25% (−32, −16)
Maximum UFP concentration (particles/cm^3)			
Road width (m)	94	6.6	28% (9, 51)
Industrial zoning (%)[b]	61	14	18% (2, 37)
Truck ratio (%)	66	2.9	9.7% (−2, 22)
Wind speed (km/h)	22	3.0	−7.1% (−21, 10)
Temperature (°C)	21	4.7	−17% (−28, −4)
Mean black carbon concentration (ng/m^3)			
Industrial zoning (%)[b]	99	14	35% (9, 67)
Road width (m)	31	6.6	17% (−8, 48)
Undeveloped area (%)[b]	13	4.0	11% (−4, 28)
Truck ratio (%)	12	2.9	10% (−9, 33)
Temperature (°C)	10	4.7	−15% (−33, 8)
Wind speed (km/h)	14	3.0	−23% (−33, 8)

PIP, posterior inclusion probability and IQR, interquartile range.

[a] Within a 25 m buffer.

[b] Within a 150 m buffer.

Industrial zoning was an important predictor of maximum UFP concentrations in multivariable models along with road width and truck ratio. Of these, road width was the strongest predictor of maximum UFP levels with each IQR increase associated with a 28% (95% CI: 9, 51) increase in maximum UFP concentration. While a strong inverse association was observed between residential zoning and maximum UFPs in single predictor models, the magnitude of this relationship decreased substantially in multivariable models and thus was not included in the final model.

Industrial zoning was the most important predictor of mean BC concentrations in multivariable models with each IQR increase corresponding to a 35% (95% CI: 9, 67) increase. Variables for road width, truck ratio, and undeveloped area were also included in the final model for BC as these factors were strongly associated with mean BC concentrations in single predictor models and the magnitudes of these associations remained strong in multivariable models. However, the coefficient for truck ratio decreased by approximately 50% suggesting that the impact of this factor on BC concentrations is partially captured by the other covariates. Residential zoning was evaluated in the final multi-variable model for BC as a strong inverse association was observed in single predictor models; however, the magnitude of this association decreased in multivariable models and thus was not included in the final model. Ambient temperature and wind speed were inversely associated with pollutant concentrations in all three final models with temperature having a stronger impact on UFPs and wind speed having a stronger impact on BC.

Sensitivity analyses using mixed-effect models with a first order autoregressive structure (AR-1) generally yielded results similar in magnitude and direction to those reported above (data not shown). The only meaningful difference noted was for the truck ratio variable in the model for mean black carbon concentration. Specifically, an IQR increase in truck ratio was associated with a stronger increase in mean black carbon concentration in the mixed-effect model ($\beta = 32\%$, 95% CI: 18, 49).

4. Discussion

In this study, we examined a number of potential determinants of near-road UFP and BC concentrations focusing primarily on road-specific attributes and land-use characteristics. In general, our findings are consistent with previous studies in Europe and North America (Abernethy et al., 2013; Hoek et al., 2011; Rivera et al., 2012) in that traffic and land use variables were important predictors of near-roadway UFP concentrations, although the specific variables examined differed between cities. In Montreal, road width, mean building height, and truck ratio were the strongest predictors of mean near-road UFP concentrations whereas road width and industrial zoning were the most important predictors of maximum concentrations. This is not surprising as traffic is a major source of UFPs in urban areas and UFPs are known to be elevated in street canyons (Nikolova et al., 2011); however, it is interesting to note that road width was a stronger predictor of maximum UFP concentrations than total traffic counts suggesting that this variable may be a reasonable replacement for traffic counts in population-based exposure models if detailed traffic count data are not available. None of the three previous land use regression studies for UFPs identified industrial zoning as an important determinant of UFPs and reasons for this are not clear; however, port proximity was identified as an important determinant of UFP concentrations in two studies (Abernethy et al., 2013; Hoek et al., 2011) likely owing to combustion emissions from ship and truck traffic in and around ports. In Montreal, the industrial zoning parameter likely reflects a mixture of both industrial emissions and regional increases in traffic in the vicinity of industrial sites. In particular, industrial zoning may be a surrogate measure of diesel traffic in a given area as this parameter was the strongest predictor of mean BC concentrations. Indeed, truck ratio was also an important predictor of mean BC concentrations in Montreal and others have also reported significant positive associations between truck traffic, industrial space, and BC in urban areas (Clougherty et al., 2013; Larson et al., 2009). Finally, while residential zoning was inversely associated with ultrafine particle and BC concentrations in single predictor models, this factor was not an important predictor of near-road UFP or BC concentrations in Montreal after accounting for other factors. This finding is in contrast to those of Rivera et al. (2012) who reported that the proportion of high density residential area was an important predictor of ambient UFPs in Girona, Spain.

While our study had several strengths including monitoring at a large number of sites with a wide range of traffic and land use characteristics over multiple days, it is important to note several limitations. First, monitoring was limited to the summer months and thus we could not develop predictive models for annual average exposures as ambient UFP concentrations are expected to be higher in the winter months owing to the well-recognized inverse relationship between temperature and ambient UFPs. In addition, potentially important factors such as restaurant or port proximity (Abernethy et al., 2013) were not evaluated as the current investigation focussed specifically on the impact of traffic and built environment on near-road UFPs and BC; these factors should be evaluated in future studies. Similarly, Hu et al. (2009) identified aircraft emissions as potentially important sources of UFP concentrations in neighborhoods adjacent to airports and this source should also be examined in future studies. Furthermore, the short time-period of monitoring in each location may be viewed as a limitation, although others have used similar methods (Rivera et al., 2012) in developing predictive models for UFPs and our monitoring was designed to capture time-periods expected to have the highest UFP and BC concentrations. Our models did not include fixed-site background concentrations as potential predictors and this may also be a limitation. However, we did include regional measures of ambient temperature and wind speed to account for the impact of meteorological changes on near-roadway concentrations. Indeed, a statistically significant inverse relationship was observed between ambient temperature and UFP concentrations and this finding is consistent with previous studies (Hatzopoulou et al., 2013; Weichenthal et al., 2008). Nevertheless, the use of regional monitors for temperature and wind speed as opposed to continuous monitors at each sampling site may have contributed to non-differential measurement error thus we may underestimate the impact of these factors on near-roadway air pollutant concentrations.

Ultrafine particles are a growing health concern but few models are currently available with which to evaluate the potential long-term health effects of these exposures. The need for such models was recently reiterated in the HEI Review Panel on Ultrafine Particles (HEI, 2013) and the factors identified in this study may be appropriate targets for the development of future models. In particular, the impact of long-term average UFP exposures on cardiovascular morbidity/mortality is arguably of most interest owing to evidence supporting the biological plausibility of an impact of UFPs on cardiovascular health (Weichenthal, 2012). Models for maximum UFPs, although useful in identify potential peak exposure areas, may be less suitable for use in chronic exposure studies as maximums occur infrequently and are less stable than average values. Future studies should also examine models predicting percentiles of exposure (e.g. 75th or 90th percentile) as illustrated by Larson et al. (2009). Regardless, city-specific models are likely required as the small number of LUR models developed to date all contain different predictor variables for ambient UFPs, although they all generally relate to traffic and local combustion sources. As a result, near-road air quality models are expected to be key elements of future studies interested in the long-term health effects of traffic-related air pollution.

Funding

Collaborative Health Research Projects, CHRP.

Acknowledgments

We would like to thank Noel Brownlie, Bernard Moulins, Julien Neves-Pelchat, Graeme Pickett, Rhokho Kim, Rebecca Luck, Nicolas Truong, and Mohamad Zukari for their excellent work in collecting air pollution and traffic data used for the analysis in this study.

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